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Granular flow in pebble bed reactors: dust generation and scaling

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Abstract – *In experimental prototypes of pebble bed reactors, significant quantities of graphite dust have been observed due to rubbing between pebbles as they flow through the core. At the high temperatures and pressures in these reactors, little data is available to understand the frictional properties of the pebble surfaces, and as a result, the Paul Scherrer Institut (Switzerland) proposes a conceptual design of a scaled-down version of a pebble bed reactor to investigate this issue in detail. In this paper, simulations of granular flow in pebble bed reactors using the discrete-element method are presented. Simulations in the full geometry (using 440,000 pebbles) are compared to those in geometries scaled down by 3:1 and 6:1. The simulations show complex behavior due to discrete pebble packing effects, meaning that pebble flow and dust generation in a scaled-down facility may be significantly different. The differences between velocity profiles, packing geometry, and pebble wear at the different scales are discussed. The results can aid in the design of the prototypical facility to more accurately reproduce the flow in a full-size reactor.*

I. INTRODUCTION

High-temperature gas cooled reactors (HTR) and very-high temperature reactors (VHTR) offer a number of safety advantages when compared to existing reactor technologies. However, prototype reactor experiments have highlighted a number of potential safety issues, such as the formation of graphite dust, where graphite parts move relative to each other, or relative to the metal parts of the reactor. The generated dust may become activated by the leakage of radioactive compounds from the fuel particles. During operation, the generated dust accumulates in the reactor core, as well as in the heat exchange system. The accumulated dust may be released if the flow is suddenly increased, such as due to a fast depressurization following a breach in the primary system pressure boundary. The characteristics and amount of the generated dust are not known, nor is its potential for release during a fast flow velocity increase.

While dust is an issue in HTRs with both prismatic and pebble bed cores, it is thought to be more significant in pebble bed cores due to the pebbles moving past one another. Other factors, such as the gas atmosphere and temperature, and the temperature inside the reactor may contribute.

Some experimental data is available on dust generation.[1] The most extensive data is from the AVR (Arbeitsgemeinschaft Versuchreaktor), an experimental pebble bed reactor that ran in Germany for approximately twenty years.[2] At the end of operation, the total dust inside the reactor was estimated at around 50 kg to 60 kg, and the median size of dust particles was smaller than 1 μm. The concentration of the dust circulating the reactor was only a very small fraction (10^{-7}) of the total. In the AVR, air and oil ingress incidents in the early years of operation are expected to have caused a large fraction of the dust generation. In addition, several different fuel designs were used in the reactor, and the earlier ones were not as durable as the later ones. Taking into account that modern graphites and fuels, as well as the plant design, differ from the ones used in AVR, the applicability of the data from AVR to modern reactor designs and graphites is limited.

The Paul Scherrer Institut has therefore proposed a project to investigate the generation of dust in modern reactor designs, as well as its characteristics, such as size, shape, and composition.[3] The project aims to construct an experimental facility consisting of a core simulator, coupled to a heat exchanger. Coupled with analytical work, the project aims to characterize the aerodynamics of the core and heat exchanger, understand the amount of dust generated and the locations most prone for deposition, and examine both normal operating conditions as well as fast depressurization events.

The core region is designed to accommodate either a pebble bed or prismatic core, although in this paper, we focus on the design of the pebble bed core. Due to cost

constraints, the experimental facility will be a scaled-down version of a full-size reactor. A suitable reference design is the pebble bed modular reactor[4] (PBMR), which features a cylindrical reactor vessel of height 10 m and diameter 3.5 m, with approximately 440,000 pebbles of diameter 6 cm. Designs in which the pebble size is kept the same, but the reactor vessel is scaled down by 3:1 or 6:1 have been considered, reducing the number of pebbles required.

However, this raises significant questions about how pebble flow in a scaled facility will compare to that in a full-size reactor. Despite a large amount of study, there is still no complete theoretical description for how dense granular materials will flow, and hence no simple way to understand how pebble flow in a scaled facility will relate to that in the full-size geometry. Granular flows have been of great interest to the engineering and geology communities, and in the past two decades have attracted renewed interest from physicists.[5,6] Their rheology is complex, allowing for a solid-like behavior and the ability to support stress, but also exhibiting a transition to liquid-like flow.[7,8] Granular materials exhibit many complexities at the level of a single particle, with forces being inhomogeneous[9,10] and concentrated along fractal-like force chains,[11] making it difficult to define a continuum theory. In the slow, dense, quasi-static limit that is appropriate for modeling the pebble bed, the packing geometry of the pebbles themselves strongly influences the flow, since in order to move, pebbles must have enough space available to rearrange with their neighbors.[12]

In the absence of a theoretical description, we have therefore carried out simulations of granular materials using the discrete-element method (DEM) in which each pebble is integrated according to Newton's laws, with a frictional contact model. Due to the stiff contact models required to simulate hard particles, DEM simulations are computationally intensive but are feasible on a parallel computer; they have been employed to analyze granular flows in many situations such as on inclined planes[13] and static granular packings,[14] and have been shown to be in good quantitative agreement with laboratory granular flows.[15] In previous work, they have also been used to analyze a variety of flow features of a full-size pebble bed reactor,[16] such as velocity profiles, pebble residence times, pebble mixing, and porosity.

In the current study, we aim to understand how flows in a scaled reactor will relate to the full-size geometry, and in particular investigate how pebble wear will differ. While the results are of direct relevance to the design of the PSI experimental facility, they also highlight the more general challenges in scaling of dense granular flows.

II. METHODS

II.A. Pebble contact model

The DEM simulations are carried out using the Large Atomic/Molecular Massively Parallel Simulator (LAMMPS) developed at Sandia National Laboratories.[17] The code is widely used and provides a framework for carrying out particle simulations interacting under a diverse variety of forces. Here, we make use of a modified version of the particle contact model introduced by Cundall and Strack[18] that is suitable for simulating frictional hard spheres of diameter d. From this, a natural simulation time scale τ can be introduced according to $\tau = (g/d)^{1/2}$, where g is the gravitational acceleration. Masses are scaled in terms of the pebble mass m. Throughout this paper, the results are specified in terms of these simulation scales, but they can be related to physical units at any time through specification of physical scales. For example, by making use of a pebble diameter of d = 6 cm, and by using g = 9.81 m s^{-2}, the time scale can be calculated to be τ = 0.0782 s. A typical mass for a pebble is m = 180 g.

The spherical pebbles interact according to a spring–dashpot contact model. If a pebble and its neighbor are separated by $\mathbf{r}$, and they are in compression, so that $\delta = d - |\mathbf{r}| > 0$, then they experience a force $\mathbf{F} = \mathbf{F}_n + \mathbf{F}_t$, where the normal and tangential components are given by

$$\mathbf{F}_n = f(\delta/d)\,(- k_n \delta\mathbf{n} + \gamma_n \mathbf{v}_n/2), \quad (1)$$

$$\mathbf{F}_t = f(\delta/d)\,(- k_t \Delta\mathbf{s}_t + \gamma_t \mathbf{v}_t/2). \quad (2)$$

Here, $\mathbf{n} = \mathbf{r}/|\mathbf{r}|$ is a normal vector at the point of contact between the pebbles. $k_{n,t}$ and $\gamma_{n,t}$ are the elastic and viscoelastic constants respectively, and $\mathbf{v}_{n,t}$ are the normal and tangential components of the relative surface velocity. Throughout this paper, the function f is defined as $f(x) = 1$ to simulate Hookean contacts. Hertzian contacts have also been considered, where $f(x) = x^{1/2}$, but the results are extremely similar and are not reported here.

$\Delta\mathbf{s}_t$ is the elastic tangential displacement between spheres, obtained by integrating tangential relative velocities during elastic deformation for the lifetime of the contact. This adds a significant computational complexity to the simulation, since it requires tracking the history of every pair of pebbles in contact. The model also makes use of a Coulomb friction coefficient μ, so that if $|\mathbf{F}_t| > \mu|\mathbf{F}_n|$ and a local Coulomb yield criterion is exceeded, then $\mathbf{F}_t$ is rescaled so that it has magnitude $\mu|\mathbf{F}_n|$ and $\Delta\mathbf{s}_t$ is modified so that Eq. 2 is upheld; this issue is discussed in more detail in the section on pebble wear.

Appropriate values of the contact model parameters have been considered in a number of previous studies. The initial calibration was carried out by Silbert et al. (Ref. 13), who found that values of $k_n = 2 \times 10^5 mg/d$ and $\gamma_{n,t} = 50\tau^{-1}$ were appropriate for simulations of granular flows on

inclined planes with 20,000 spheres up to a height of approximately 40d. This value of k_n is significantly softer than for typical hard materials like glass, where a value of $10^{10}mg/d$ would more appropriate. However, since the simulation time step must scale according to $k_n^{-1/2}$, it is not computationally feasible to use a physically realistic value, and the value of $2 \times 10^5 mg/d$ was found to be a reasonable compromise, correctly capturing the granular dynamics without creating prohibitively large elastic oscillations.

In the previous full-size simulations of pebble bed reactors,[16] these values were adopted, and were sufficient to carry out a variety of analyses. However, subsequent work has shown that the above parameters can lead to spurious vertical oscillations in velocity that grow in significance at higher points in a drainage simulation.[15] These oscillations occur very rapidly, and it was found that they only had a weak effect on macroscopic flow features such as velocity profiles. However, beyond a height of around 60d, they had a significant effect on microscopic quantities that were measured, such as autocorrelations in pebble velocity. Since one of the main aims of the current study is to investigate the microscopic quantity of wear, a value of k_n of ten times larger than previous work was considered, which was shown to mitigate the vertical oscillations. To accommodate this, the time step was decreased by a factor of four, which remains feasible given progresses in a computer technology.

Table I summarizes the typical parameters used throughout this study. The value of k_t is chosen based on considerations of the Poisson ratio of the pebble. The values of the viscoelastic constants are scaled up by a factor of $10^{1/2}$ for consistency, to preserve the same coefficient of restitution for two pebbles colliding in free space. Throughout this paper, we make use of a friction coefficient of $\mu = 0.5$. While the friction coefficient of graphite may vary greatly at different temperatures and when it becomes irradiated,[19–21] this value is within a reasonable range; we aim to study the friction dependence in more detail in the future.

Table II provides details of the computations, listing the typical number of processors used for each run and the total number of pebbles. The full-size simulations are by far the most computationally expensive, and were carried out at the Swiss National Supercomputing Centre on ROSA, a Cray XE6 system with 47,872 cores. All other simulation runs were carried out on a variety of Linux machines and Mac Pros. In general, due to the short-range force model where pebbles only interact when they are in contact, the code exhibits high parallel efficiency and doubling of processors will reduce the simulation time by almost half. Memory and disk usage are relatively small, with processor power being the limiting factor.

TABLE I

Contact model parameters used in the simulation

Simulation parameter	Value
Normal elastic constant k_n	$2 \times 10^6 mg/d$
Tangential elastic constant k_t	$2k_n/7$
Normal viscoelastic constant γ_n	$(50 \times 10^{1/2})\tau^{-1}$
Normal viscoelastic constant γ_t	$(50 \times 10^{1/2})\tau^{-1}$
Friction coefficient μ	0.5
Time step Δt	$2.5 \times 10^{-5}\tau$

TABLE II

Parameters describing the simulation lengths and geometries

Parameter	Full-size	3:1	6:1
Number of pebbles	440,000	16,500	2,050
Exit pipe radius r_p	5d	3.5d	2.5d
Exit pipe height z_p	10d	3d	2.5d
Reactor radius r_r	29d	10d	5d
Insertion height z_i	180d	60d	30d
Wear cutoff height z_w	135d	45d	22.5d
Insertion rate R_i	$774\tau^{-1}$	$86.6\tau^{-1}$	$19.0\tau^{-1}$
Pouring time t_P	750τ	1,000τ	250τ
Drainage time t_D	2,750τ	9,000τ	9,750τ
Snapshot interval	2.5τ	2τ	0.5τ
Typical processors	256	4	2

II.B. Geometry and initial packing generation

The reactor geometries are specified in a cylindrical (r,θ,z) coordinate system with gravity pointing in the negative z direction. The reactor is composed of several wall objects that are added to the simulation, with pebble–wall interactions being handled with the same contact model as pebble–pebble interactions. In a real reactor, the walls are made of graphite with different properties than the pebble surface, and typically the pebble surface is expected to be softer than the walls. However in the absence of any data for the properties of the specific graphites that are used, the pebble–wall friction coefficient was chosen to match the pebble–pebble friction coefficient for all simulations.

To carry out the scaling study, three different reactor geometries have been considered, and the parameters describing these are given in Tab. II. Firstly, a full-size simulation with 440,000 pebbles, matching the same geometry as the previous study[16] and based on the MPBR has been carried out. A 3:1 scaled geometry with 16,500 pebbles and a 6:1 scaled geometry with 2,050 pebbles have been also been considered. For each of the three geometries, the reactor is composed of a cylindrical exit pipe of radius r_p that extends downwards from $z = z_p$. The top of the exit pipe is joined to a funnel at a slope of 30° to

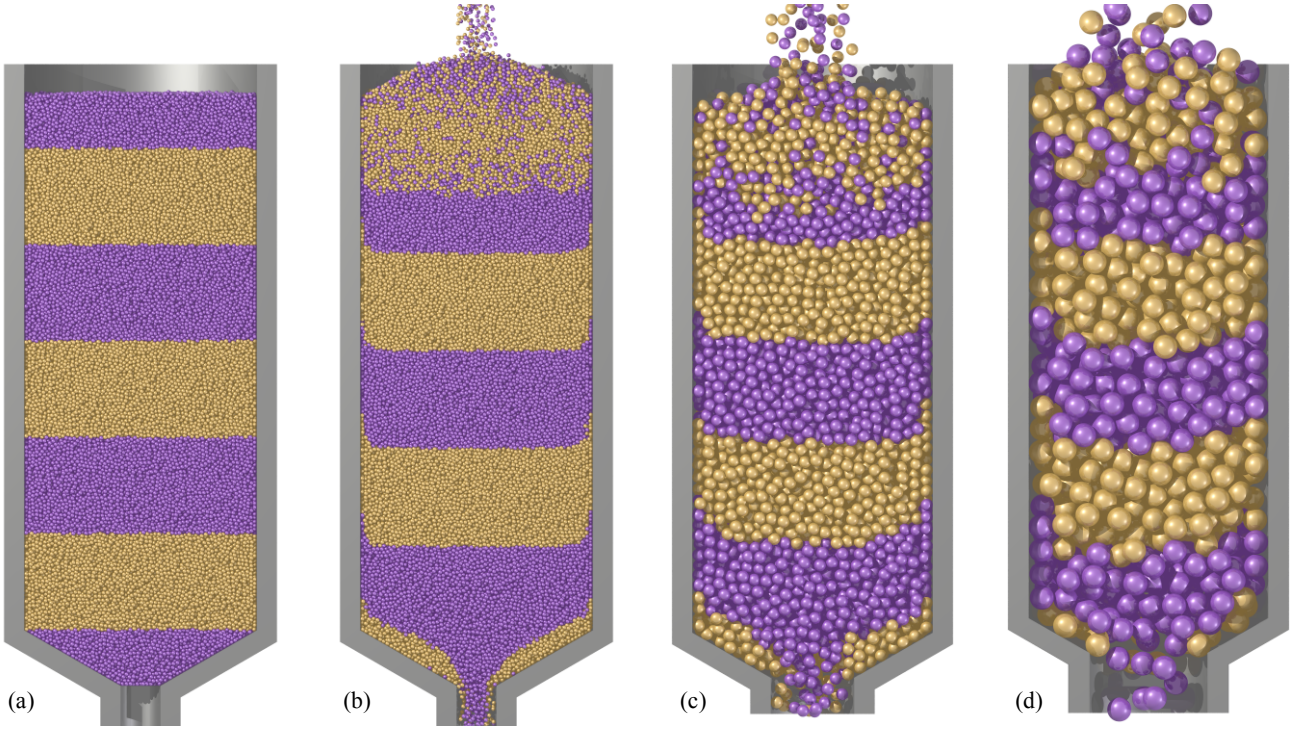

Fig. 1: Snapshots of (a) the full-size geometry prior to the initiation of flow; and (b) the full-size geometry, (c) the 3:1 geometry, and (d) the 6:1 geometry during flow. A central slice through each geometry is shown, by only plotting those pebbles with $y > 0$. The snapshots during flow are shown at 717.5τ, 86τ, and 33τ respectively, corresponding to when 20% of the pebbles have drained. Before drainage is initiated, the pebbles are colored in vertical bands of width 24d, 8d, and 4d respectively, and the deformation of the bands highlights the pattern of flow; the two colors of pebbles are mixed together at the top of each simulation due to intermingling during the reinsertion.

the horizontal, which meets the cylinder of radius r_r that forms the main reactor vessel.

It should be noted that some immediate challenges are faced with constructing the scaled geometries. For the full-size geometry, an exit pipe of radius $r_p = 5d$ is used. However, it is well known that granular flows have a tendency to jam when the outflow pipe is less than 5d in diameter, and thus the natural values of r_p in the scaled geometries would be too small. They have therefore been chosen to be 3.5d and 2.5d for the scaled runs to avoid this problem. Furthermore, granular materials tend to have lower packing densities near walls due to additional pebble ordering,[22] and thus the number of pebbles in the 6:1 is slightly smaller than what would be expected based on volume scaling alone.

For each of the geometries, initial pebble packings are then created by plugging the exit pipe with a horizontal wall at $z = z_p$, and then randomly raining pebbles in from a fixed height of z_i at a given rate R_i; details of this process can be found in previous work.[14,22] Each simulation is run for an interval t_P that is long enough for all pebbles to be inserted and come to rest. At the end of each simulation, a snapshot of the exact pebble configuration is stored, which includes information about all of the tangential displacements $\Delta\mathbf{s}_t$ at pebble contacts that feature in the history-dependent contact law.

II.C. Pebble drainage

For each of the initial pebble packings, a drainage simulation is carried out by removing the horizontal wall plugging the exit pipe, and letting the pebbles fall out under gravity. The flow rates under gravity are typically a lot faster than would be expected in real reactors, where a mechanism is employed to remove pebbles, and a flow rate of one pebble per minute would be more reasonable. However, previous work has shown that for dense granular flows in the quasistatic regime, the overall flow rate has a weak effect on the features of flow, allowing for time to be scaled out. This is because at slow flow rates, kinetic effects play a weak role, and geometrical features of how pebbles flow past one another largely determine the flow. In particular, work by Choi et al. has shown that the amount of particle diffusion in slow, dense granular drainage experiments is invariant over a large range of flow rates.[23] It is therefore reasonable to expect that the results can be connected to a real reactor by scaling the time variable by an appropriate factor.

A custom routine was added to the simulation that recycles pebbles falling out of the exit pipe by reinserting them at the top of the packing. After every one hundred timesteps, any pebbles that have fallen into the region $z < 0$ are removed and randomly reinserted into the disk $z = z_i$ and $r < r_p$. The recycling routine requires cooperation between many processors in the simulation, since pebbles have to be gathered across several processors. The operation must also ensure that the reinserted pebbles do not overlap with existing ones, and hence it is more efficient to carry out every hundred timesteps rather than continuously. To avoid a buildup of pebbles within the disk, which would prohibit further insertions, the recycled pebbles are given an initial downward velocity of $6d/\tau$ in the full-size simulation and $3d/\tau$ in the 3:1 and 6:1 simulations.

The overall pebble flow rates are $124\tau^{-1}$, $41.6\tau^{-1}$, and $14.2\tau^{-1}$ for the full-size, 3:1, and 6:1 geometries respectively. Snapshots of the pebble positions are saved at intervals of t_s, which can be post-processed to carry out a variety of analyses. In addition, a diagnostic routine to analyze pebble wear is carried out within the simulation during the contact force computation – this is discussed in more detail below.

II. FLOW PROFILES AND PEBBLE ORDERING

Figure 1 shows snapshots of the simulations at the different scales. In Fig. 1(a) the initial pebble packing in the full-size simulation is shown. In this initial packing, the pebbles are colored in vertical bands of width $24d$. Figure 1(b) is taken from the same simulation at a time of 717.5τ after the onset of drainage, after which approximately 20% of the pebbles have drained and been recycled. The deformation of the colored bands gives an indication of the pebble motion. The lowest purple band is strongly deformed and some pebbles in this band have exited and been recycled, indicating increased velocities in the region directly above the exit pipe. This is confirmed by Fig. 2(a), which shows that the vertical velocity profiles become more pronounced nearer the exit pipe.

The higher purple bands show much less deformation, and are almost horizontal in the bulk, corresponding to pebbles falling like a plug with very little rearrangement. At the reactor wall, a small boundary layer of slower pebbles is visible over a length scale of approximately $4d$ due to friction with the reactor wall. This is confirmed in the velocity profiles shown in Fig. 2(b), which are almost uniform across the bulk of the reactor, with a small region of slower velocity near $r = 29d$.

Figures 1(c) and 1(d) show snapshots of the 3:1 and 6:1 simulations after 86τ and 33τ respectively, which also correspond to around 20% of pebble drainage. In general terms, the deformations of the bands are similar to the full-size simulation. However, it can be seen that the boundary layers of slower velocity occupy a larger fraction of the

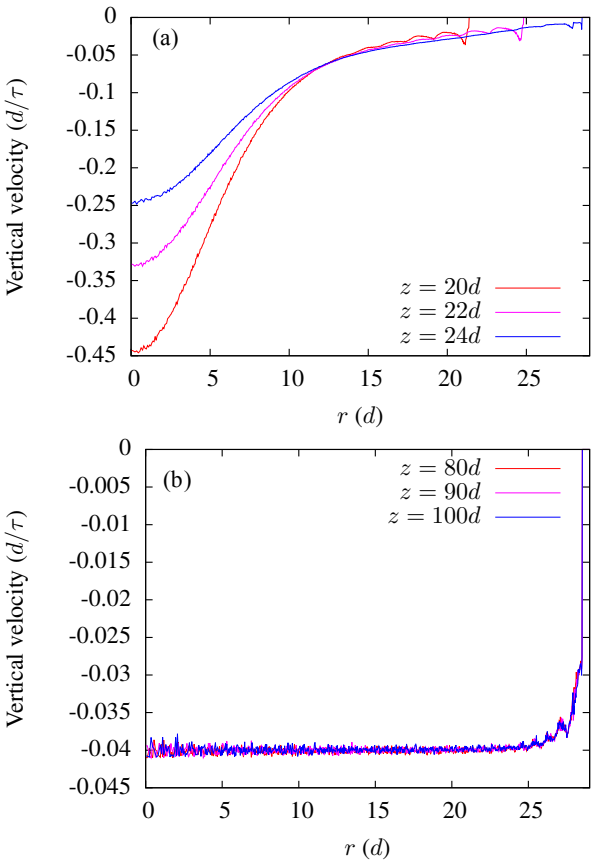

Fig. 2: Profiles of the vertical velocity component in the full-size simulation at (a) several heights in the converging region of flow above the exit pipe, and (b) several heights in the middle of the reactor.

reactor. To investigate this in more detail, the normalized velocity profiles were computed, by scaling the radial coordinate by the reactor radius r_r and normalizing the velocity by the total flux. The results, shown in Fig. 3(a), highlight that the boundary layers of slower flow are proportionally much more significant in the scaled geometries.

This is because the size of the boundary layer is driven by geometrical considerations: it will take up roughly the same number of pebble diameters regardless of the overall reactor size. To highlight this more clearly, the number density was computed for each simulation – this is defined as the number of pebble centers per unit volume. As shown in Fig. 3(b), the number density exhibits strong peaks in the full-size geometry near $r = 29d$ corresponding to pebbles being ordered into layers against the wall that slip past one another during flow; similar orderings have been seen in other studies.[14–16] The ordering takes up roughly the same number of pebble diameters in the scaled geometries. In the 6:1 geometry, the ordering of pebbles into layers is visible even into the center of the reactor.

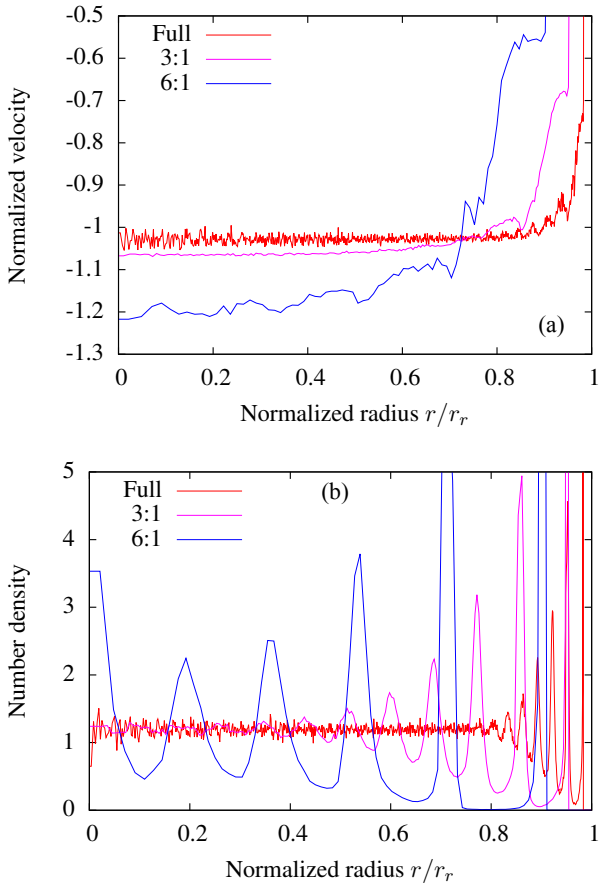

Fig. 3: Plots of (a) number density and (b) normalized vertical velocity for the three simulations.

III. PEBBLE WEAR

III.A. Computation of wear

As the pebbles flow through the reactor, they will slide against each other and against the reactor walls, causing wear and generating graphite dust. This section aims to quantify this dust generation, and determine how it is spatially localized.

Quantifying the amount of wear between two surfaces is a research field unto itself, and a very large number of models are discussed in the literature. Many of these models are summarized by Meng and Ludema,[24] who note that the general picture of wear is complex and poorly understood, citing how wear has been proposed to be a function of a great number of physical variables. For the current study, the situation is particularly unclear, since the properties of graphite at high temperature are not well known. A recent survey article[25] noted that wear rates differing by several orders of magnitude have been reported, depending on the experimental conditions; little data is available for conditions similar to the reactor, and the influence of factors such as pebble sliding velocity or contact force have not been researched in detail. Since we are unable propose a model that may take into account the particular properties of graphite, we therefore make use of the classical model of Archard,[26] which is one of the simplest available. In this model, the volume of worn material is given by

$$W = ksP/p_m \tag{3}$$

where s is the sliding distance, P is the applied load, and k is a dimensionless parameter. The quantity p_m is referred to as the "flow pressure", has units of pressure, and is roughly equivalent to a material hardness. For the purposes of this study, k and p_m are assumed to be unknown constants, and thus the amount of wear is measured in terms of sP with units of energy, $dm^2\tau^{-2}$.

The wear model of Archard was also made use of by Cogliati and Ougouag in their pebble simulations,[27] where slip was computed in terms of the relative tangential velocities between pebbles. In the contact model employed in these simulations, presented in Eqs. 1 and 2, the amount of slip can be naturally quantified by making use of the tangential displacement $\Delta\mathbf{s}_t$.

Consider two pebbles that are in a horizontal plane and are constrained so that they cannot rotate. Suppose the pebbles are brought into contact, and then one pebble is slowly displaced vertically by small amount. This will create an elastic tangential restoring force $\mathbf{F}_t$ given by Eq. 2. If the restoring force is below the Coulomb friction criterion, so that $|\mathbf{F}_t| < \mu|\mathbf{F}_n|$, and the pebble is allowed to freely move in the vertical plane, then the combination of the elastic and viscoelastic tangential forces will cause the pebble to move back to its original position of contact, where $\Delta\mathbf{s}_t = \mathbf{0}$. Thus this type of contact can thought of as elastic and reversible, with no slip occurring.

Now suppose that as the pebble is displaced vertically, there is one instant when the elastic tangential restoring force exceeds the Coulomb friction criterion. In that case, the tangential displacement will be modified, so that $\Delta\mathbf{s}_t$ is replaced by $\Delta\mathbf{s}_t + \mathbf{c}$ for some vector $\mathbf{c}$. If the pebble is allowed to move freely in the vertical plane, then in a similar manner to described previously, it will move back to where $\Delta\mathbf{s}_t = \mathbf{0}$. However, this will be displaced by a vector $\mathbf{c}$ from its original point of contact.

Hence, a modification of $\Delta\mathbf{s}_t$ due to the friction law corresponds exactly to the case when irreversible slip occurs between pebbles. This provides a succinct way to evaluate wear within the simulation: every time a pebble contact is evaluated, an additional step can be carried out to compute an amount of wear as the product of $|\mathbf{F}_n|$ and the magnitude of the modification to $\Delta\mathbf{s}_t$. Wear can also be computed at a pebble–wall contact using the same procedure.

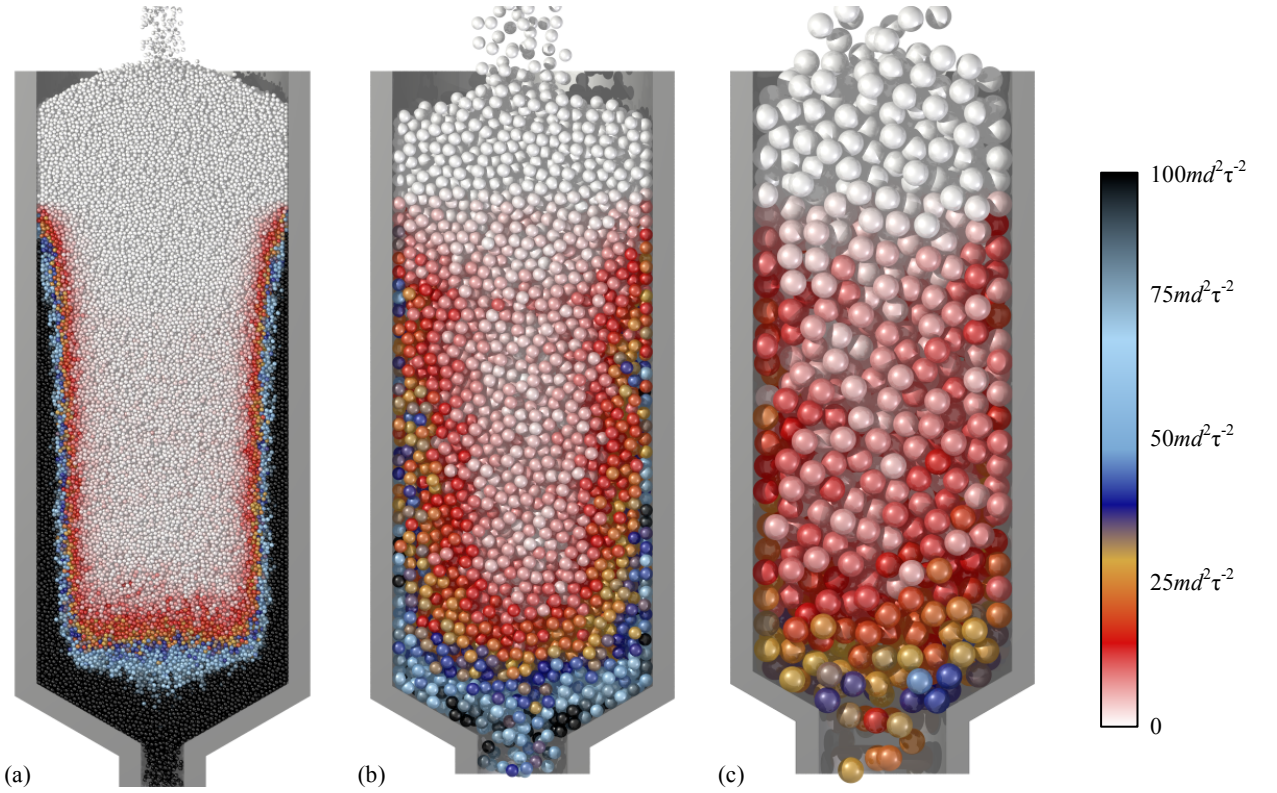

Fig. 4: Snapshots of (a) the full-size geometry, (b) the 3:1 geometry, and (c) the 6:1 geometry at 717.5τ, 86τ, 33τ respectively, corresponding to when 20% of the pebbles have drained. Each pebble is colored according to the amount of wear is experiences under the Archard model, being measured in units of work. Wear is not recorded for pebbles above $z > z_w$, to avoid counting a large amount of wear due to mixing in the reinsertion region.

III.B. Wear per pebble

For each pebble within the simulation, the amount of wear that it experiences as it flows through the reactor can be calculated by summing up all its individual wear contributions at each timestep. This data can be used to evaluate how different pebbles flowing through the reactor experience different amounts of wear, which may affect how they are recycled.

However, before proceeding, one difficulty has to be addressed: the simulations record a large amount of wear occurring at the top of the packing, as pebbles are reintroduced, fall under gravity, and undergo many collisions as they come to rest at the top of the packing. In a real reactor design, it would be expected that there would be a much less intensive method of reintroducing pebbles, perhaps by the use of a mechanism to individually place them at the top of the packing. Because of this, it was chosen to discount any wear occurring in the topmost region, and only record wear below in the region $z < z_w$. The values of z_w for the three simulation geometries are shown in Table II.

Figure 4 shows snapshots of the full size, 3:1, and 6:1 simulations after approximately 20% of the pebbles have been drained, where the pebbles have been colored according to the amount of wear they have experienced. In the full-size geometry it can be seen that the pebbles in the bulk experience very little wear. This agrees with the results of Sec. II, where this region was shown to be in plug flow with very little rearrangement, and hence very little pebble slip. In the boundary layers of slower flow, a significant amount of pebble wear is visible as the pebbles slide past one another. A large amount of wear is also visible in the converging region of flow above the exit pipe, since a large amount of pebble slip must occur. It can also be observed that in this region, there are significant variations from one pebble to another, showing that wear will not be particularly evenly distributed; this may be linked to the large variations in force that are frequently present in granular materials.[9–11]

In general, the patterns of wear are qualitatively similar for the 3:1 and 6:1 geometries, although since the boundary layers of slower velocity take up a larger fraction of the reactor, there is a smaller region of plug flow where pebbles experience very little wear.

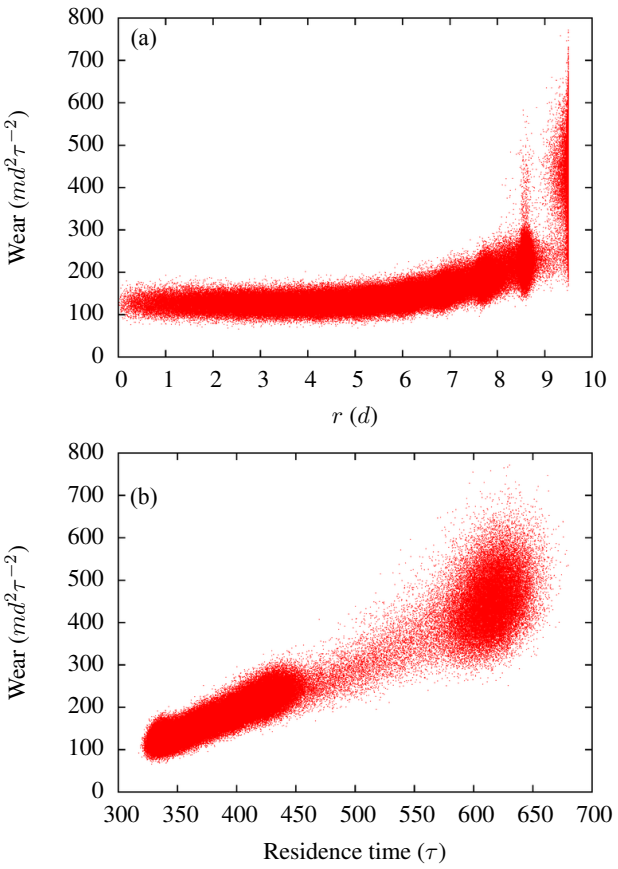

Fig. 5: Plots of pebble wear in the 3:1 simulation (a) as a function of radial coordinate when passing z_w, and (b) as a function of residence time.

III.C. Correlations in pebble wear

Figure 5(a) shows a scatter plot of each pebble's radial position as it passes $z = z_w$, versus the total amount of wear it accumulates as it passes through the reactor, for the 3:1 simulation. The plot shows that there is high correlation between these two variables, and a high probability that a pebble reinserted close to the wall will experience more wear. In the experimental facility, this may be a useful method of altering which pebbles are worn: reinserting more heavily worn pebbles in the center of the reactor will lead to an more even distribution of pebble wear, while reinserting more heavily worn pebbles will lead to wider distribution, and may be useful mechanism to create and test heavily worn pebbles. Figure 5(b) shows a scatter plot of wear versus the residence time of each pebble, showing that these two variables are also closely correlated, suggesting that in a real reactor, the amount of fuel burn-up that a pebble receives may be correlated with the amount of wear it experiences.

IV. CONCLUSIONS

The DEM simulations that we have carried out have demonstrated that granular flow in a scaled-down facility bears some qualitative similarities to a full-size geometry, but that there are some serious issues, most notably that the boundary layers of slower flow near the reactor walls will take up a much larger fraction of the flow. In a 6:1 geometry, there is no region that could be described as being in plug flow where pebbles experience little rearrangement.

These preliminary results suggest many avenues of investigation and we are currently extending this study to examine a wider variety of pebble flows and geometries. For this study the value of friction of $\mu = 0.5$ was used, but given the ambiguity in frictional properties of graphite, it may be worthwhile to understand how friction affects the results. We are also planning to investigate how the magnitude of forces that the pebbles experience will vary at different scales.

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